Progress Report USGS 04HQGR0047

Episodic Tremor and Slip in Northern Cascadia

H. Dragert, G.C. Rogers, J. Cassidy, H. Kao, and K. Wang
Geological Survey of Canada
Pacific Geoscience Centre
9860 West Saanich Road,
Sidney, B.C. V8L 4B2

Phone: 250-363-6447
Fax: 250-363-6565
dragert@pgc.nrcan.gc.ca
http://www.pgc.nrcan.gc.ca

Key Words: Seismotectonics, Source Characteristics, Surface Deformation, GPS-Continuous

Investigations Undertaken:

1. Seismic data and continuous GPS data from the existing seismic and continuous GPS networks dating back to 1997 have been re-examined to corroborate the one-to-one correlation of tremor and slip for Vancouver Island. These data were reviewed in detail to help define the source regions and the return period for Episodic Tremor and Slip (ETS), especially to the north of the area where ETS was first discovered (Rogers and Dragert, 2003).
2. Improved tremor locations were determined using the Source Scanning Algorithm (SSA) developed by Kao and Shan (2004) and the temporal evolution of tremor and slip was examined for the March 2003 episode of ETS.
3. A field program deploying 10 additional broad-band seismometers and 5 additional GPS receivers was carried out from April to August, 2004, to provide more detailed observations of ETS.

Results:

Review of Past Data

A review of the available continuous digital seismic data from stations of the Canadian National Seismic Network located on Vancouver Island enabled the identification of tremor occurrence in northern Vancouver Island. This extends the mapped region of ETS to the northermost part of the Cascadia margin where the Explorer Plate converges with the North America Plate. A comparison of tremors in this region, designated as "NI" in Figure 1, with the ETS events identified for southern Vancouver Island (SI) and northwestern Washington State (Rogers and Dragert, 2003) has revealed the following:

Table 1: Summary of Observed Long (>5da) Tremor Sequences

South Island			*North Island*		
Date	Julian Day	Days Between Tremors	Date	Julian Day	Days Between Tremors
04/29/97	119		02/04/98	35	
06/28/98	179	425	04/09/99	99	429
08/14/99	226	412	03/18/00	77	434
12/02/00	336	475	08/22/01	234	522
02/02/02	33	427	09/15/02	258	389
02/25/03	56	388	11/25/03	329	436
Means:		425	424		
Sigmas:		32			66

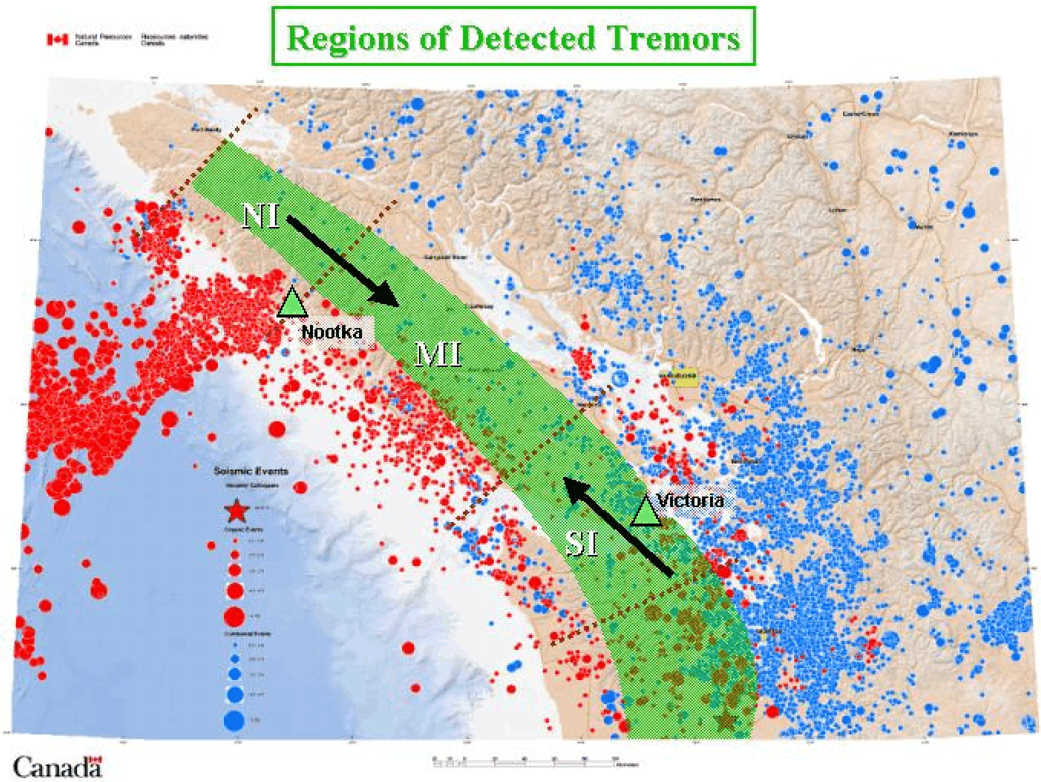

Figure 1. Distribution of earthquakes and tremors. This figure shows regional earthquakes in the subducting Juan de Fuca oceanic slab (red circles) and the overlying North America crustal margin (blue circles) recorded between 1985 to 2002. Green shaded region shows general area of tremor occurrence on Vancouver Island and the Olympic peninsula. NI, MI, and SI indicate arbitrary divisions of Northern, Mid, and Southern Vancouver Island for tremor counts. The black arrows show the dominant direction of tremor migration for the SI and NI regions. Triangles show the locations of the two GPS sites whose data are displayed in Fig. 2.

1. The average return period of extended (>5 days) episodes of tremor are identical in both regions, averaging about 14 months (see Table 1 and Figure 2). For comparison, the most recent estimate of the return period for GPS-observed episodic slip in south Vancouver Is. is 447 +/-37 days which is based on 8 slip episodes (Dragert et al., 2004). However, if the same subset of 6 ETS events is used, the GPS-based average return period becomes 425 days, identical to the tremor-based estimate.
2. The occurrence of NI and SI significant episodes of tremor are not in phase (see Figure 2). ETS in the southern region lags north-island tremor by approximately 6 months.
3. The speed of the migration of tremor along strike of the subduction zone is about 5 to 10 km per day in both regions. However, for the south island the direction of travel is predominantly from southeast to northwest, whereas for the north island, almost all tremor episodes initiate in the northernmost region and propagate southeast.
4. GPS coverage in northern Vancouver Island is sparse and is unable to constrain models of slip. However, the data from a recently established continuous GPS station at Nootka Sound (NTKA) show the expected transient westward displacement of a few millimetres at the time of the last three tremor episodes (Figure 2).

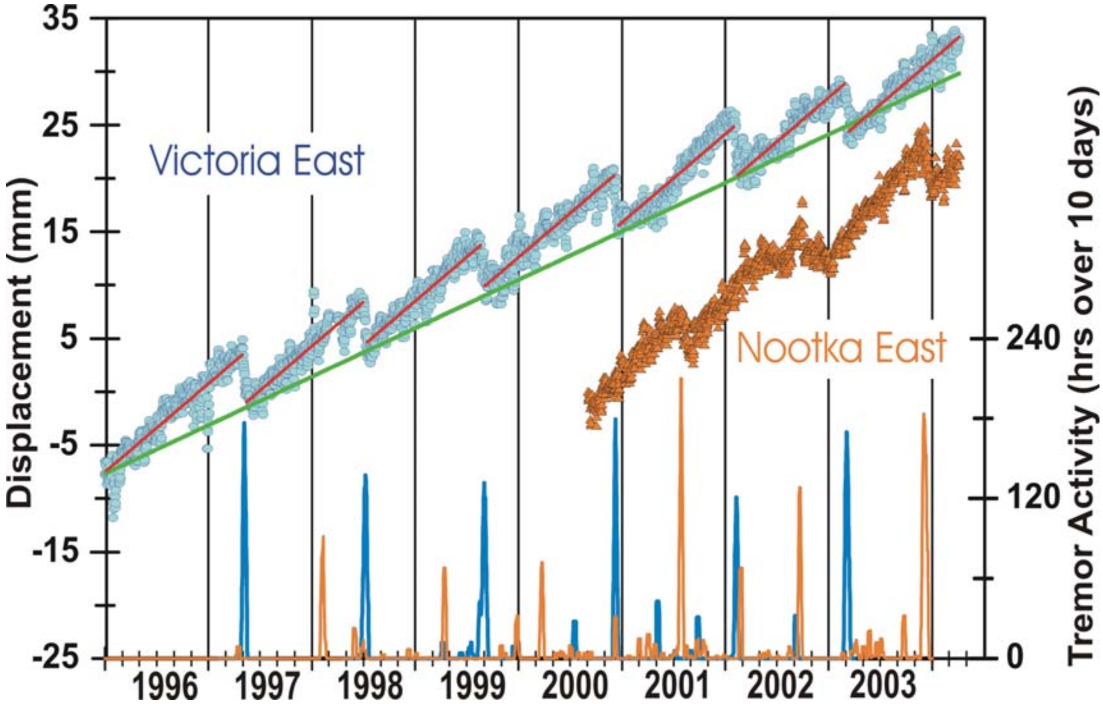

Figure 2. Crustal displacements and tremor episodes observed in southern and northern Vancouver Island. Daily changes in the longitudes of the GPS stations at Victoria and Nootka (with respect to the GPS reference station at Penticton) are shown by the blue circles and the orange triangles respectively. The blue graph shows the total number of hours of tremor activity in a sliding 10-day period (a 10-day window was used since it was the nominal duration of a slip event) for southern Vancouver Is. and the orange graph the same but for northern Vancouver Is. Tremors were also found to occur at times between slips, but tremor activity at such times was substantially less. The coincidence of transient westward displacements at times of tremor episodes in each respective region is clear.

The conceptual model for ETS in southern Vancouver Is. can be summarized as follows (Dragert et al., 2004). Stress accumulates episodically across the deeper (25 to 45km) plate interface beneath Vancouver Island in the direction of plate convergence. This deeper stress is relieved every 13 to 16 mo over periods of several weeks, marked by distinct seismic tremors and transient surface displacements that migrate along strike of the subduction zone. The fact that ETS activity is similar for northern and southern Vancouver Is. suggests that the recurrence interval for ETS is not dependent on convergence rate since Explorer Plate convergence at 2 cm/yr is half that of Juan de Fuca Plate convergence. For southern Vancouver Is., modeled episodic slip can account for ~2/3 nominal plate rate motion. GPS coverage in the north is too sparse to derive meaningful slip models needed to estimate the amount of slip. The out-of-phase occurrence of ETS and the preferred opposite directions of ETS migration in these two regions remains unexplained.

Detailed Analysis of the March 2003 Tremor Episode

Because of their emergent nature (see Figure 3), tremors lack distinct phases that can be correlated from station to station thereby making source locations difficult to estimate with the same precision as regional earthquake locations. To overcome this problem, we have used the "Source Scanning Algorithm" (SSA) developed by Kao and Shan (2004) to determine energy source locations for tremor pulses. The concept of this technique is illustrated in Figure 4.

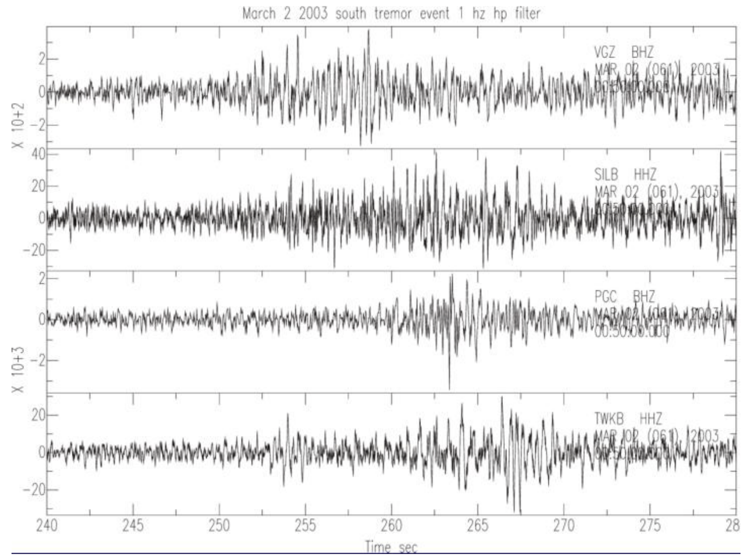

Figure 3. Sample of tremor records. Shown here are 40s of tremor activity in the vertical velocity component recorded at 4 sites and passed through a 1Hz high-pass filter. The southernmost station (VGZ -Victoria) is at the top, and the northernmost (TWKB– Youbou) is at the bottom. Recorded activity is reminiscent of lower frequency 'wind noise' except that the energy envelope moves out coherently across the network.

With reference to Figure 4, we start with a 3-dimensional shearwave velocity model with a 1 km 3D grid. For a given time segment, the scanning process first calculates the theoretical arrival times from one grid point inside this velocity model to all seismic stations. The corresponding absolute amplitudes at all stations at the respective expected arrival times are stacked to give the "brightness" for that grid point. This calculation is systematically repeated for all grid points to image the snapshot of seismic sources in the region at that particular time. The scanning then proceeds to the next time segment. The process is applied recursively: First with a scan at a time interval of 5s with a spatial resolution of 1 km to identify coherent seismic events, and subsequently at shorter time intervals (down to 0.1 s) to locate the "brightest" spot. Generally, a unity-normalized brightness of 0.8 is used as a lower limit and values below this level are assumed to be background noise. Tests on synthetic data indicate a SSA resolution capability of better than 3 km (Kao and Shan, 2004).

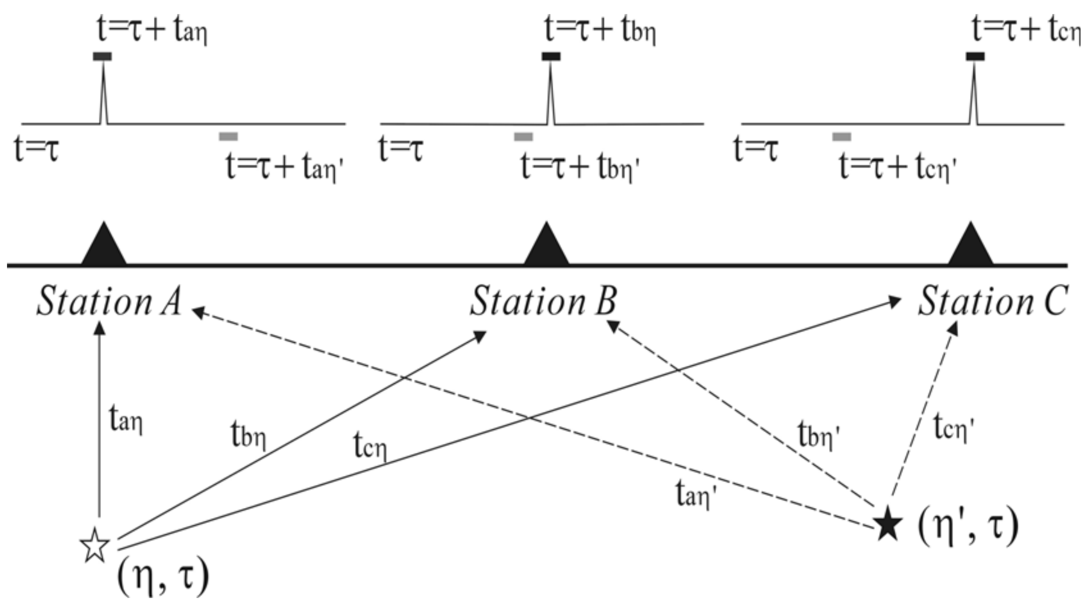

Figure 4. 3D source scanning algorithm to image seismic sources of earthquakes or non-earthquake origins. In this simple illustrative example, we assume at a time τ there is a "source" at location η but not η', resulting in the simple seismograms at stations A, B, and C with amplitude spikes at times depending on the travel times from η to the stations. Stacking these amplitudes will result in a high "brightness" being assigned to (η, τ) but not (η', τ) (from Kao and Shan, 2004).

The location and along-strike progression of tremors for the March 2003 sequence are shown in Figure 5. Feb. 25 is designated as Day 0 and the ovals show the 1-sigma geographic distributions for certain days of the sequence, labelled D2 to D24. Both the migration and area of tremor is identical to previous ETS episodes in this region, moving from southeast to northwest and covering a region overlying the 25 to 45 km depth contours of the subducting plate interface. The most significant finding from the SSA analysis is the depth distribution of tremor sources (Figure 6). Tremor depths range from 10 to 45 km, greatly exceeding the errors associated with SSA. This provides the first evidence that tremor is not limited to a narrow fault zone coincident with the plate interface, raising the question of whether the relief of stress characterized by crustal displacements during ETS may also be caused by distributed shear instead of slip on the deep fault interface.

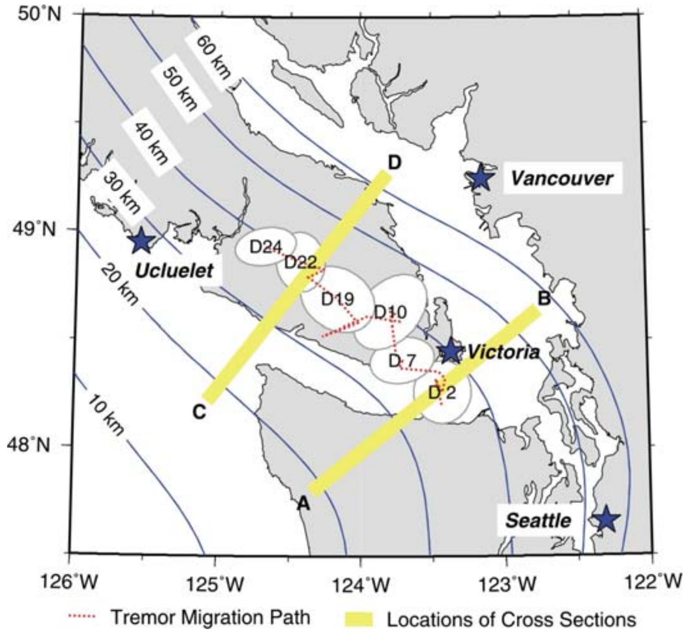

Figure 5.. Distribution and migration of March 2003 tremors. The oval regions represent the 1-sigma geographic tremor distribution on selected days. The days are designated sequentially with Feb. 25 set to Day 0. The path of the daily centroid of tremor activity is given by the red dotted line. The average speed of along-strike migration is about 7 km/day. The lines AB and CD show the location of cross sections displayed in Figure 6.

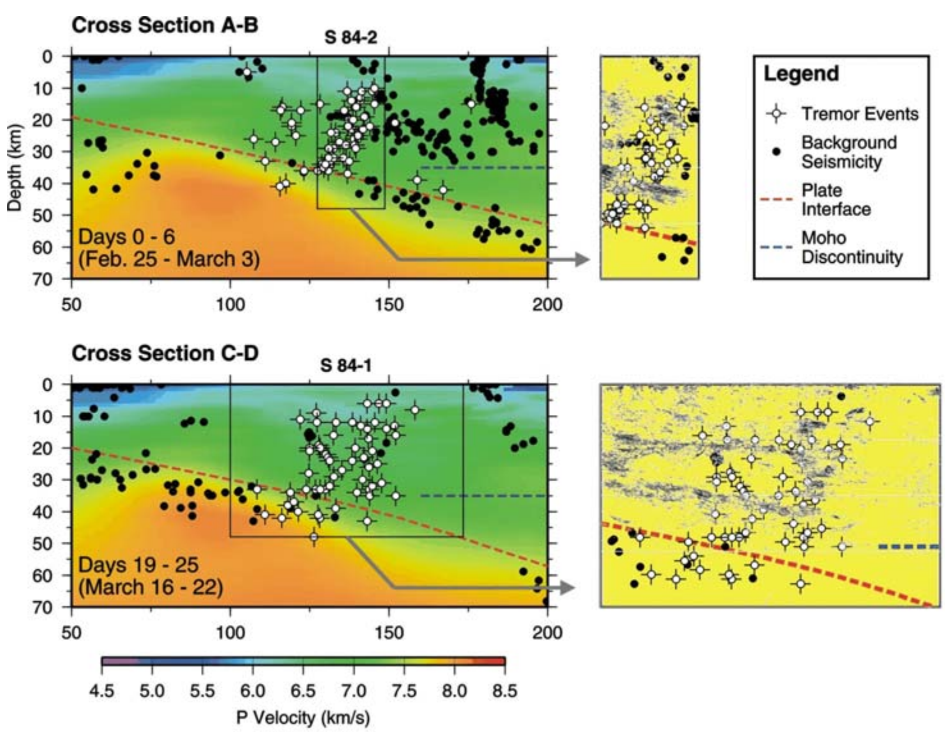

Figure 6. Vertical distribution of tremors from SSA. Location of cross-sections are shown in Fig. 5. P-velocity model is from Ramachandran (2004).The magnified panels to the right show shear reflectors identified in previous seismic studies (Nedimovic et al., 2003).

July 2004 Field Observations

In April 2004, existing seismic stations of the Canadian National Seismic Network (CNSN) and those deployed under the POLARIS (Portable Observatories for Lithospheric Analysis and Research Investigating Seismicity) program were augmented by 10 broadband seismometers on Vancouver Is.. To improve crustal deformation monitoring, 5 temporary continuous GPS were also deployed to densify the coverage of the existing Western Canada Deformation Array (WCDA). The targeted EPS episode occurred from Jul. 8 to 24 and the additional instruments were kept in operation until Aug. 16. These data are currently being analyzed and will prove critical in corroborating our findings from the March 2003 ETS episode.

Non-Technical Summary

The examination of past seismic and continuous GPS data for Vancouver Is. shows that Episodic Tremor and Slip occurs all along the northern Cascadia margin, including the region of the Explorer Plate. The return period of tremors in northern Vancouver Is. is the same (~14.5 months) as in the southern region, indicating that ETS recurrence rate is not dependent on plate convergence rate. The mapping of tremor source locations using the Source Scanning Algorithm shows an extended depth distribution which suggests that slip may also be distributed, or slip and tremor are caused by separate but linked processes.

Reports Published

Dragert, H., K. Wang, and G. Rogers, Geodetic and seismic signatures of Episodic Tremor and Slip in the northern Cascadia subduction zone, *Earth Planets and Space*, Proceedings of the 2nd International Symposium on Slip and Flow Processes in and below the Seismogenic Region, Mar. 10-14, 2004, Univ. of Tokyo, Japan, in press, 2004.

Kao, H., and S. Shan, The Source-Scanning Algorithm: mapping the distribution of seismic sources in time and space, *Geophys. J. Int.*, **157**, 589–594, 2004.

Data Availability

GPS data: Daily 30sec data files in Rinex format at http://www.wcda.nrcan.gc.ca or via anonymous ftp from wcda.pgc.nrcan.gc.ca

Tremor data: Upon request - Contact Honn Kao at hkao@NRCan.gc.ca

References

Dragert, H., K. Wang, and G. Rogers, Geodetic and seismic signatures of Episodic Tremor and Slip in the northern Cascadia subduction zone, *Earth Planets and Space*, Proceedings of the 2nd International Symposium on Slip and Flow Processes in and below the Seismogenic Region, Mar. 10-14, 2004, Univ. of Tokyo, Japan, in press, 2004.

Kao, H., and S. Shan, The Source-Scanning Algorithm: mapping the distribution of seismic sources in time and space, *Geophys. J. Int.*, **157**, 589–594, 2004.

Nedimovic, M.R., R.D. Hyndman, K. Ramachandran, and G.D. Spence, Reflection signature of seismic and aseismic slip on the northern Cascadia subduction interface, *Nature*, **424**, 416-420, 2003.

Ramachandran, K., S.E. Dosso, G.D. Spence, R.D. Hyndman, and T.M. Brocher, Forearc Structure Beneath Southwestern British Columbia: A 3-D Tomographic Velocity Model, *J. Geophy. Res.*, in press, 2004.

Rogers, G.C., and H. Dragert, Episodic tremor and slip on the Cascadia Subduction Zone: The chatter of silent slip, Science, 300, 1942-1943, 2003.